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INVESTIGATION OF GAZE PATTERNS IN DAYLIT WORKPLACES: USING EYE-TRACKING METHODS TO OBJECTIFY VIEW DIRECTION AS A FUNCTION OF LIGHTING CONDITIONS

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Abstract

Despite numerous efforts in developing glare indices through human assessment studies, predicting visual comfort in indoor environments still poses important challenges in design. A major limitation in discomfort glare indices is that they all ignore its dependencies on view direction. In this study we adopted eye-tracking methods in a series of human assessment experiments in order to record actual visual response when experiencing discomfort glare. We set up an experiment where the view directions distributions were monitored as the participants were working in a side-lit office with three different task-supports - monitor, paper and phone - on a standardized office task sequence. The participants were allocated randomly to two groups where they were exposed to two different views from the window. The results show that the "view outside the window" is the main determinant of view direction bias whenever the participant is not focused on any cognitive or visual office task procedure.

Keywords: Daylighting, Office lighting, Discomfort Glare, Eye-tracking

1 Introduction

The importance of well daylit and glare free indoor environments has become unquestionable. Daylight has dynamic qualities that enhance appraisal and acceptability of the space (VEITCH 2001) (NEWSHAM, et al. 2005) (OSTERHAUS 2005) while elevating the occupants' well-being and health (WEBB 2006). The dynamic changes in intensity and spatial distribution of daylight interacting with the indoor environment's form and physical properties create contrast variations over the space. These contrast variations in the indoor environment can change from commonly appreciated highlights to disturbing light variations over the field of view. The latter situation fosters a recognized type of visual discomfort known as discomfort glare (COBB, MOSS 1928) (VOS 1999) (VOS 2003), which "causes discomfort without necessarily impairing the vision of objects" (CIE. 1995).

There is a general consensus that discomfort glare is one of the prevalent sources of potential dissatisfaction for the occupants in indoor environments and one of the main causes for manipulation of the shading systems by the occupant. This has proven discomfort glare to be an important issue for daylighting design. However, when it comes to the practical level, designing for a glare free daylit indoor space is still a major barrier.

The initial challenge with this phenomenon is that it only creates subjective negative responses with no immediate visual strain and no known physiological origins (BOYCE 2004). Studies have associated discomfort glare with certain pupil fluctuation (FRY, KING 1975) and activities of facial muscles in vicinity of the eye (BERMAN, et al. 1994). Though, it is not certain that the mentioned observations are indications of a general discomfort, or that they are created by the actual discomfort glare sensation (STONE 2009) (HOWARTH, et al. 1993). So far, conventional human assessments have been used in studies to quantify discomfort glare by means of questionnaires with focus on the negative responses. These studies were mostly done under artificial lighting conditions, with the exception of one research project that was made under daylit conditions (WIENOLD, CHRISTOFFERSEN 2006). Despite biased subjective responses when view out of a window is available (resulting in higher glare tolerance) (TUAYCHAROEN, TREGENZA 2007) or task difficulty is increased (resulting in lower glare tolerance) (SIVAK 1989) (ÖSTBERG, et al. 1975), the quantification attempts on discomfort glare have led to the development of a series of different indices for visual comfort predictions in indoor spaces. Each of these glare indices evaluate glare differently but they share a basic trend and are drawn upon the same four physical quantities: the glare source luminance, size and location in the field of view, and the general field of luminance that the eye adapts to.

Recent studies, trying to compare different glare indices (CORREIA DA SILVA, et al. 2012), emphasize the necessity of fundamental change of approach behind these indices and their basic form (CLEAR 2012) due to some major limitations. One of the major limitations of the current indices regarding daylit situations relates to glare source size and location in the field of view (CLEAR 2012). The sensation of discomfort varies greatly depending on the angular displacement of the glare source to the view direction (LUKIESH, GUTH 1949) (IWATA, et al. 1991) (KIM, et al. 2009). View direction is where we direct our gaze by mutually moving our body, head and eyes yet discomfort glare assessments are made with the assumption of a fixed view direction. Another view direction dependent parameter, which is measured in different ways among various glare indices with the same fixed view direction assumption, is adaptation luminance.

Very few studies so far have investigated the relationship between view direction distributions and visual comfort in office settings. These studies suggest that the view directions are mainly attracted by stimuli connected with the work task or a moving object and primarily resting on the window when taking a break from computer work (HUBALEK, SCHIERZ 2005) (SURRY, et al. 2008). However, these studies do not investigate the relation between the view directions and discomfort glare sensation. On the other hand, research efforts have been made to account for the uncertainty an adaptive capability of view direction shifts in response to uncomfortable conditions by (somewhat arbitrarily) extending view directions to a predefined angular range (JAKUBIEC 2012) rather than a unique view direction, though without any attempt to relate to actually experienced view direction patterns.

Integrating the dynamics of view direction distribution in discomfort glare assessments requires to resort to eye-tracking methods, which have only marginally been used in lighting studies so far. New advances in eye-tracking methods have opened up opportunities to investigate view direction distributions in realistic scenarios. The observations on view direction distributions enables us to account for correct angular displacement of glare source in relation to the actual dominant view directions and adaptation luminance while catching other glare induced visual responses such as blinking. These observations may also demonstrate how a luminous daylit environment can cause the negative individual responses either by attracting the eye towards excessive bright areas (VOS 2003) or by inducing continuous deviation of the eye with similar neurophysiological pathways as photophobia (STONE 2009). Either way, the hypothesis is that certain ranges of luminance values cause certain view direction shifts, thus creating predictable view direction patterns over the indoor space. To predict these patterns based on luminance values, can represent the "sweet spots" of the indoor space as a basis for a glare free design solution.

This paper presents the outcomes of a series of experiments where we investigated the view direction distributions in relation to "view outside the window" and "office task" under a real daylight situation. We gathered the photometric data and the view direction data while the participants were performing a sequence of standard office tasks with three different task-supports (monitor, paper and phone). The results are presented here where we show that the main inclination of view directions is towards the view outside the window when the participants are not focusing on the task area. We can also see that neither the different task-supports, nor the two different selected views from the window had a significant effect.

2 Methodology

The adopted approach relies on a series of user studies set up. In a previous study (SAREY KHANIE, et al. 2011), a series of experiments were done as a pilot study that aimed to observe the effect of different light conditions on eye movements. This study, which served as pre-experimental planning phase, was the first step in integration of the eye-tracking method into the experiments with determination of influential variables on view direction distributions. Four different light conditions (ranging from dim and low contrast to bright and high contrast) were produced in an office-like test room for this initial study which resulted in four different levels of visual comfort experienced by the participants while they were performing an office task. The results indicated that the effect of different light conditions were different for different office tasks, meaning that while the participants were not focused on a certain task such as reading from a monitor screen, the view direction distributions were mainly affected by the light conditions in the room. Building upon these findings, a new series of experiments were conducted with a specific focus on view outside the window and office task-support in daylit situation with low luminance contrast (no direct sun penetration). The experiments were made under real daylight conditions in an office-like test room where the participants performed a series of well-defined office tasks. The office tasks included four phases – Input, Thinking, Response, and Interaction- and were performed on three different task supports: monitor-screen, paper and phone. The task supports were iterated randomly for each participant. Two different views from the window were also iterated between the two groups of participants. Photometric quantities relevant to visual comfort were gathered. The participants' eye and head movements were recorded by means of an eye-tracker.

2.1 Experiment setting

The experiments were performed in an office-like side-lit module located on top of a four story building in the southwest of Germany in Freiburg, starting from late February until end of May 2012. The module is 360º rotatable so as to allow reasonably repeatable experiments for varying sun positions. The sky conditions ranged from overcast to clear but the module was always positioned so as to exclude any direct penetration of sunlight (low luminance contrast). The office is a single workstation. We arranged the layout so that the desk was situated perpendicular to the window with 60 cm distance from the window and 150 cm from the wall behind, falling into the standard minimum space requirements for a single office station (NEUFERT, 2012). The glazing type is a double glass with a light transmission of 54 %, a U-value of 1.1 W/m²K, and a total solar energy transmission of 29 %. Indoor light distribution was monitored by lux meters and calibrated CCD cameras equipped with a fish-eye lens used as a multiple point luminance-meter. From the participants' view perspective the two cameras were positioned to assess the 270° luminance distribution variations over the duration of each trial using luminance mapping with high dynamic range (HDR) imaging techniques. The HDR imaging together with a fish eye lens enables us to measure the luminance vibrations over a large field of view with high resolution. The cameras were situated above the participants' head and were adjusted according to each participant's height while seated. The view direction distributions were measured by means of a mobile eye-tracker that records participants' both eye and head movements for accurate view direction positions in the 3D space (Fig. 1).

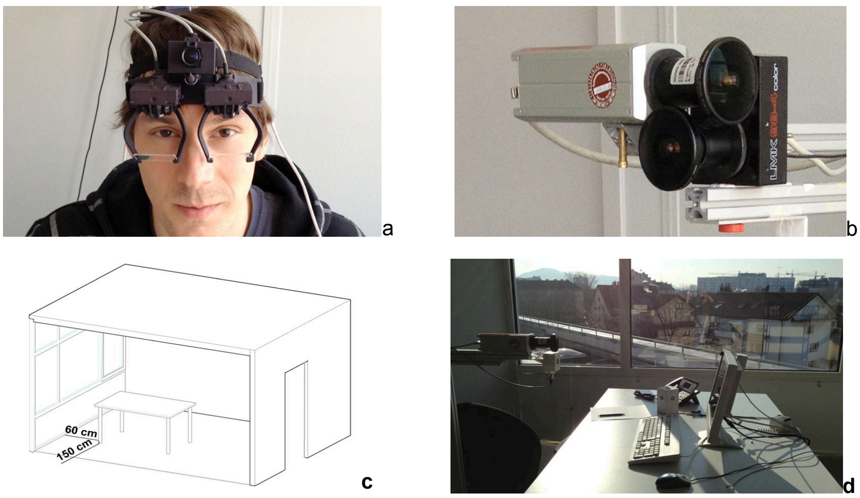


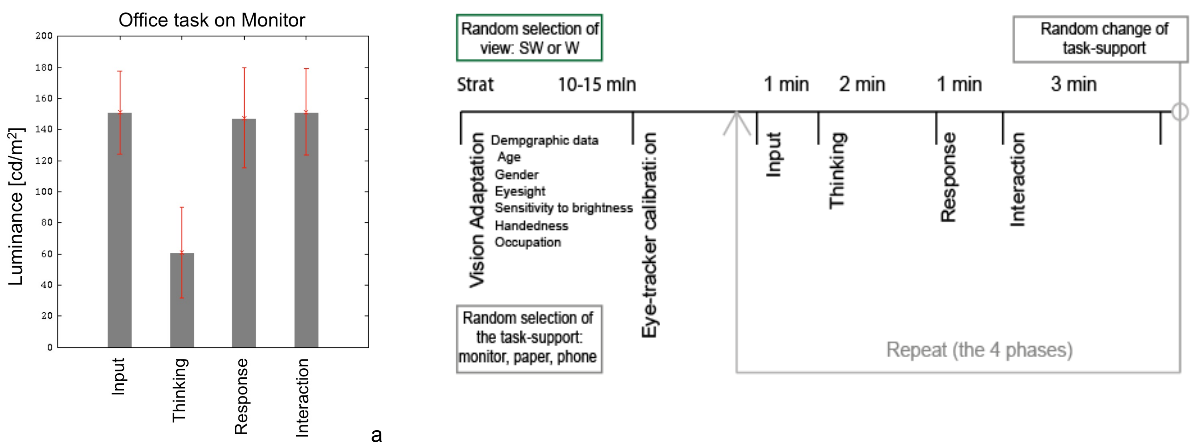
Figure 1 – The experimental set up: a) A participant wearing the eye-tracker, b) The LMK luminance cameras taking two 182° fish eye image for a 270° range every 30 second, c) 3D section of the single office room layout, d) An image of the room.

2.2 Test Procedure

During the test each participant was exposed to a randomly selected experimental trial. Each trial was divided into three task blocks. In each task block the participant performed a standardized office task using one out of three different task-supports: monitor screen, paper and phone. Each task blocks consisted of four main phases: “Input”, “Thinking”, “Response”, and “Interaction”. The flow of phases for “on-screen” task were as follow:

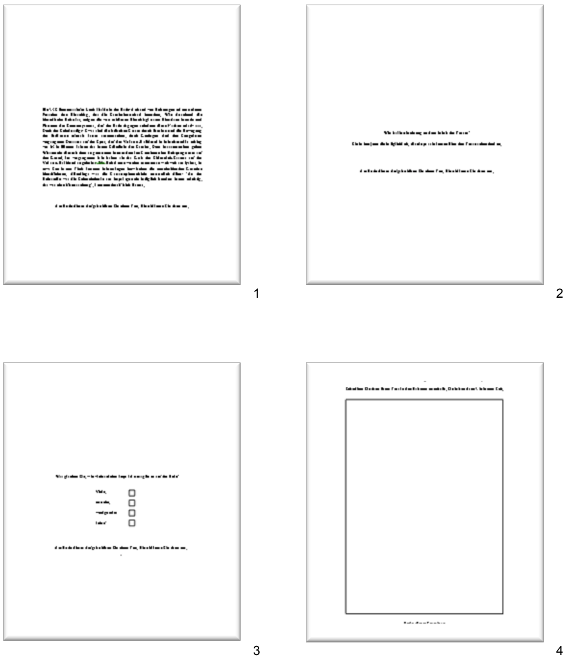
During the “Input” phase of the on-screen task event, the participant would read a text from the monitor screen which is visually a highly demanding office task. This phase was followed by the “Thinking” phase, with duration of 2 minutes. For this phase the participant was asked to think about the information he/she received during the previous phase. The monitor was turned off as to minimize the interaction with the task-support, allowing for non-task orientated eye movements with the average luminance value falling in average from 127.6 to 57.54 cd/m^2 (Fig. 2a) Thereafter, during the “Response” phase the participant was asked to answer a multiple-choice question related to the information he or she had received during the “Input” phase. The last phase of this trial was “Interaction” during which the participant were asked to process and produce an opinion about the “Input” information, and then to convey this opinion though interaction with the task support by typing it on the screen in the designated area. The last two phases encourage a realistic flow of office task where both visual and cognitive performance is required. The on-paper trial followed the same procedure except that all the tasks were performed “on-paper”. This also applies to the “on-phone” task block where the four phases were carried out on the phone (Fig. 2b). The trial duration was standardized so that each block took seven minutes: input phase 1 minute, thinking phase 2 minutes, response phase 1 minute and 3 minutes for the interaction phase. Each trial started with the participant entering from the outside, first through the neighboring module, and then to the test scene so as to have a similar eye adaptation processes to indoors light. Before the start of the trial, the eye-tracker was calibrated for each participant.

The performed office tasks were within a certain range of difficulty in order to account for effects of task difficulty on discomfort glare (SIVAK 1989) (ÖSTBERG, et al. 1975) while having a visual and cognitive level close to a real office task procedure. The input text was chosen randomly among 12 different paragraphs for each task block. The text paragraphs were selected carefully from articles of easy reading level in German, providing information on a commonly familiar topic. The texts were chosen with a text difficulty that could be read in 1 minute. During the monitor screen task block, the visual consistency of the reading task for all participants was insured by standardizing its appearance on the monitor screen based on ergonomics of human-system interaction (ISO/FDIS 9241-303 2008). In order to avoid uncontrolled skimming or skipping that occurs naturally when reading a continuous paragraph (LEGGE 2006), the text was adjusted and set to the centre of the monitor screen and paper during each respective task blocks. For the on screen task block, an LCD monitor was used, as it is the most commonly used type of monitor in the office environments.



a b

Figure 2 – a) Monitor screen luminance variations during the block, b) the procedure of the experiment



a b

Figure 3 – a) In each trial the participants were performing a sequence of office tasks in three blocks using the monitor screen, the paper and the phone, b) Each block consisted of four phases: b1) First, the input text, was presented to the subject; b2) Then instructions were given to initiate the thinking phase; b3) Then the multi-choice question was posed based on the content of the input text; b4) Finally, a designated area was presented for typing/writing when working with computer or paper

2.3 Participants

23 participants, 17 males and 6 females, in the age group of 20 to 50 were recruited under consent from the Fraunhofer-ISE staff to participate in the experiment. All participants were German speakers to avoid any bias due to lack of comprehension of the text in the input phase. The participants' head position in the room was then measured and they were asked to keep the correct distance from the monitor screen during the trail. Demographic data were gathered for each person. Among the 23 participants, 8 had corrected eyesight and only 2 considered themselves sensitive to brightness.

2.4 View

The two views from the window were selected among the range of possible views towards south. The two selected views extended to a far distance with a varying mixture of artefacts and natural elements and were both high in diversity (Fig. 4). Both views fall into the category that is most appreciated by office workers (HELLINGA, 2010) (TAUYCHAROEN, 2007) with minor differences from each other. The two views are separated by a 45°angle, ranging from a southwestern to a western direction. At the participant's position the relative overlap of the views is 47 %.


a


b

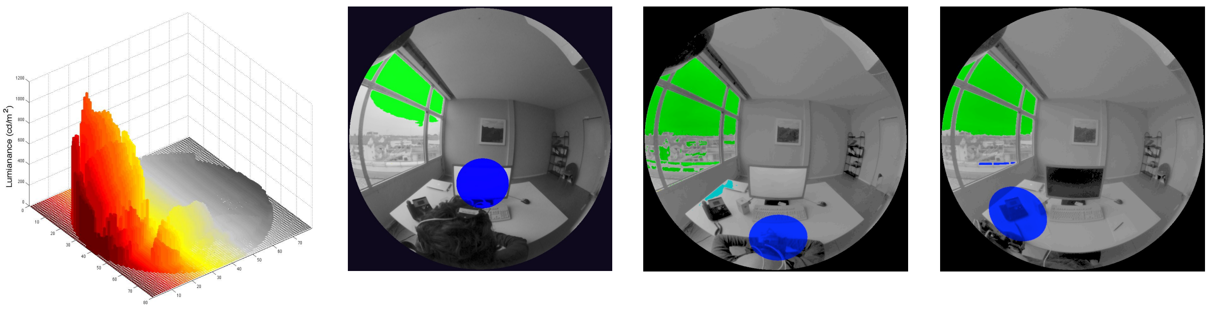
Figure 4 – a) southwest view outside the window b) west view outside the window

2.5 Eye-Tracker

In a three-dimensional scene, visual perception occurs as result of fixating view direction on an object or scene region. This occurs through a combined shift of eye, head and body movements. The eye movements in the space would tell too little about the actual view directions. In order to account for all these movements and get an accurate view direction we adopted a mobile eye-tracker, EyeSeeCam (Fig. 1a), a state-of-the-art eye tracker (SCHNEIDER, et al. 2009) that records head centered data. Integration of the inertia data of the head movements, offers the transformation to actual 3D scene reference view direction coordinates. The mobile ESC minimally limits the participant's movements and allows for natural exploration of the scene.

2.6 Light variations

For the current experimental setting it is important that the light variations are minimal over the course of the experiment and fall into a low contrast level. We evaluated the luminance contrast of the scene based on luminance measurements made every 30 seconds (Fig.5a). The luminance values that exceed 5 times the average luminance of the task area (Fig.5b) was determined using the Evalglare glare source search algorithm (WIENOLD, CHRISTOFFERSEN 2006). The selected threshold value is arbitrary and is selected through trial and error. The average luminance of these peak luminance regions was then divided by the average luminance of the scene to account for small changes in contrast (Equation 1,2).



a | b

Luminance distributions | Task area on screen | Task area on paper | Task area on phone

Figure 5 – Example showing the luminance distribution

Luminance contrast was calculated as

$$C_l = \frac{\sum_i L_{s,i} \times \omega_{s,i}}{L_a} \tag{1}$$

where

- C_l is the luminance contrast over the scene with the assumption that the point of focus is on the task area
- L_s are the peak luminance regions with five times higher luminance than the task area weighted by their size
- ω_s is the size of the high luminance region in solid angle
- L_a is the average luminance of the scene as follow:

$$L_a = {}^{1}\!/_{2\pi} \sum_i L_i \times \omega_i \tag{2}$$

where

- L_i is the luminance value of a pixel (cd/m^2)
- ω_i is the size of the pixel in solid angle (sr)

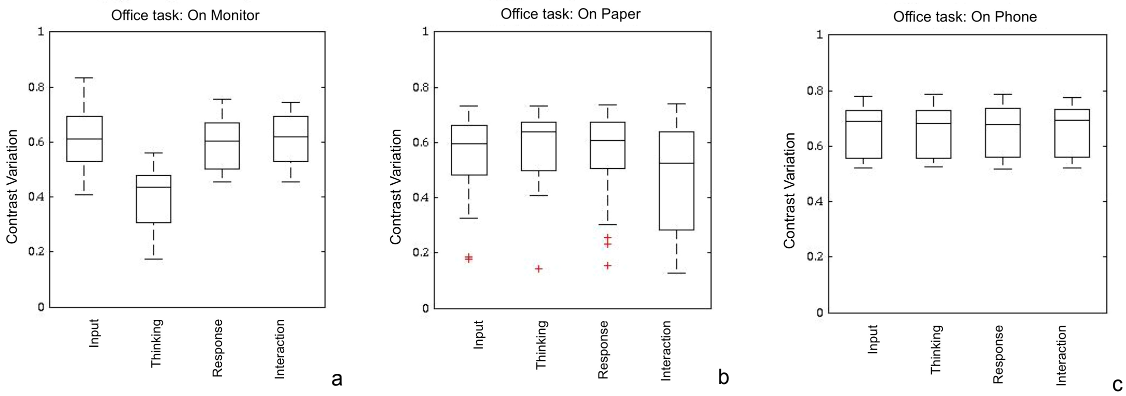


Figure 6 – Luminance contrast occurrence during different task blocks: Graphical bloxplot representation of the contrast and its variation. The box represents 50% of the data and the outer borderlines 95% of the data. a) During the thinking phase of the on-monitor block, the monitor screen turns off which lowers significantly the general luminance contrast. b) Certain large variations of contrast can be seen due to participants' change of position while working with paper. c) The inconstancies seen in the previous blocks are not apparent in this phase. The screen is off and the participant holds a stable position

The results demonstrate the consistency that is a requisite for the participant grouping under the clear or overcast sky for lower contrast lighting conditions. The luminance contrast variations over the whole trial for 50% of the participants lie between 0.6 and 0.8 while all are below 1, staying at consistent and low luminance contrast variations. There are certain changes in variation due to events such as the monitor screen turning off during the on-monitor task block (Fig 6(a)) or possible change of positions by the participant while writing on the paper during the on-paper task block (Fig 6(b)). In both cases the decrease in the luminance of the task area results in the detection of lower peak luminance values, which consequently lowers calculated luminance contrast. The detection algorithm thus needs to be refined for a fixed luminance value of the task area in order to avoid these inconsistencies.

3 Results

3.1 Eye-tracking results

The effect of view outside the window, task-support, and office task phases were addressed in the analysis of the eye-movement data. As the view direction is spatially distributed and two-dimensional, the radial standard deviation from the center of the distribution is a liable measure to give distinct descriptions of the effect of each of these factors. Radial standard deviation is fundamentally a quantity defined as, the square root of the total sum of squares of the deviations in the horizontal and vertical directions from their respective sample distribution centers, divided by the number of points of impact. The center of the data was determined using data clustering techniques. To quantify the effects of the independent factors being a three way ANOVA was performed on radial standard deviation of the view directions. The factors were view outside the window(view south-west, view west), task-support (monitor screen, paper work, call on phone), and office task phase (input, exploration, response, interaction). There was an effect of office task ($F= 14.17, p<0.001$) and task support ($F=7.96$, $p<0.005$). The effect of the two views outside the window was not significant ($F=4.6$, $p>0.03$), which means that the participants looked at the two different views in a similar manner. The small interaction between task-support and task phases indicates a probable difference of view direction distributions while having the on-phone task-support.

3.2 Dominant view direction distributions in the room

The dominant view directions were determined by organizing the view direction data in 73 bins on horizontal axis and 37 bins on the vertical with a 5° spread. The angular positions of the bins with maximum values was then considered as the dominant view directions of the task block. As seen in the ANOVA results, the view direction distributions were mainly determined by the office task and the task-support that was used to perform the task. Otherwise, if the participants were not focusing on the the task the view directions were

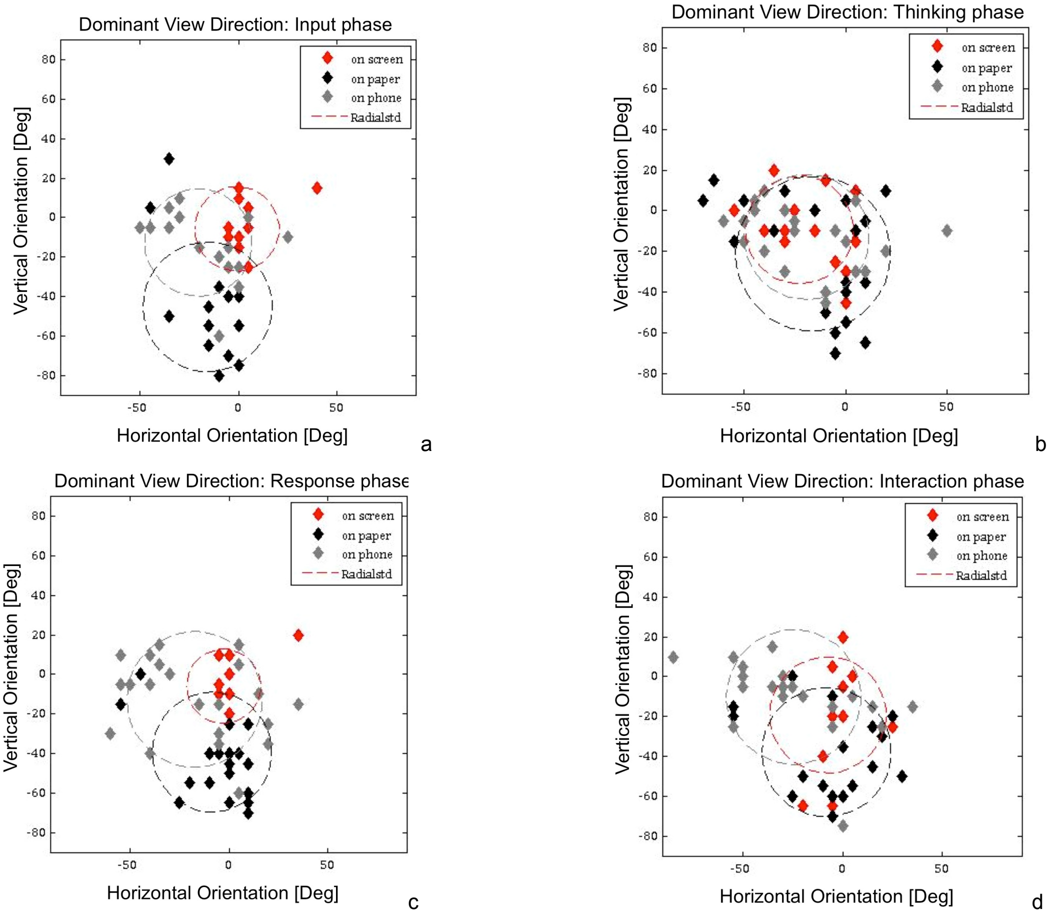


Figure 6 – a) While working with different task-supports, the view directions are mainly around the task area and less distributed, b) The view directions spread widely during the explorations phase with a clear tendency towards the view outside the window, c,d) The two last phases require certain level of engagement in both visual and cognitive task. During these two phases we can see the wider distribution of view directions with inclination on both task and view.

orienated towards the view outside the window. Another possible interpretation is that during cognitive parts of the task, while the participant is thinking about the answer or the opinion, they would rest the view direction on the view outside the window. The dominant view direction distributions show little significance for either view. The comparison between the two distinct phases of input and thinking, being respectively the task-focused phase and the visual exploration phase (Fig 7(a, b)), as well as the view direction distributions during the whole trial, shows this clearly (Fig7c).

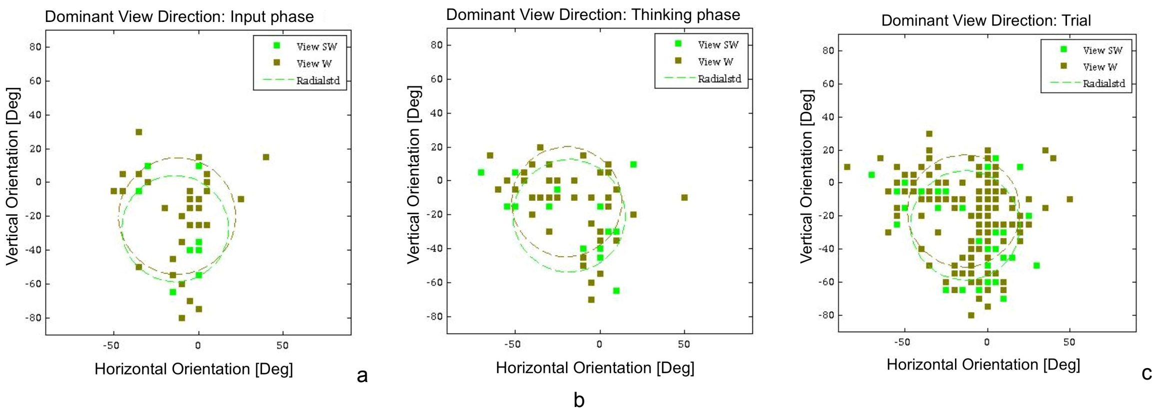


Figure 7- we do not find any significant difference between the chosen views outside the window.

4 Discussion and Conclusion

In this paper, we investigated the dominant view direction distributions in a daylit office-like test room while the participants were performing on standardized office tasks. High contrast and glare situations were avoided by choosing respective daylight conditions for the experiments. View direction measurements for two groups of participants exposed to two different views from the window were made. It can be concluded that, under a controlled lighting condition with a low spatial contrast variations, over the course of four office task phases, the view directions are directed towards the view outside the window if there is no task being performed. The results also show that, the different task-supports had no significant effect. Whichever the medium of interaction, participants intend to focus the view directions on a defined visual task independently of the surrounding situation. The task area luminance value is thus a good measure for the eye adaptation luminance during visually focused office tasks as the view directions are focused on the task area. The participants' view direction distributions in relation to the selected views outside the window show that the participants have looked at either of proposed views in a similar manner, and neither chosen views had a significant effect on the view direction distributions.

This experiment was designed to establish a foothold for the usage of eye-tracking methods for better understanding of the view direction in the room as a function of luminance variations. Based on the present findings, a second phase of experiments will be developed with different daylight conditions to understand the effect of light variations, e.g. low versus high contrast. The iteration between the two studied views would make it possible for the repetition of the future measurements without unwanted biases. The findings regarding dominant view direction measures make it easier to identify the glare source position displacements accurately with respect to the line of view direction and adaptation luminance in glare assessments. Ultimately, analysis needs to be done to calculate discomfort glare including dynamic view directions with participants' subjective assessments.

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